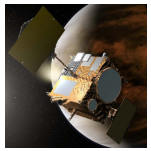

AAS 17-331

JPL Navigation Support for the JAXA Akatsuki (Planet-C) Return to Venus

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Jet Propulsion Laboratory
California Institute of Technology

27th AAS/AIAA Space Flight Mechanics Meeting
San Antonio, Texas February 8, 2017

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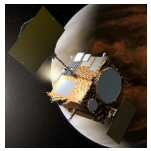
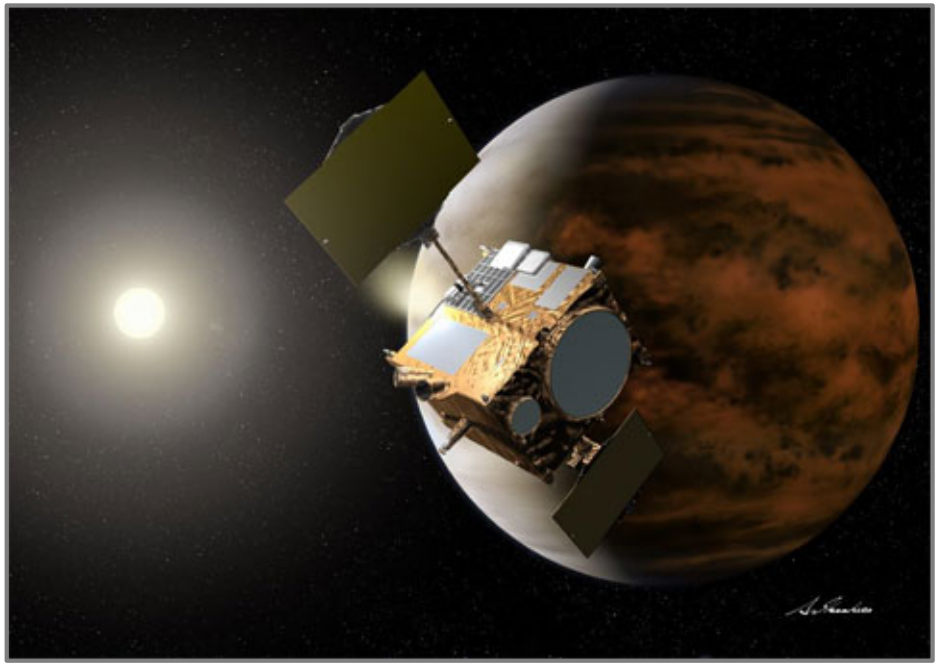
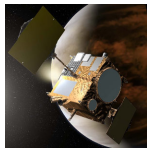


Planet-C Mission

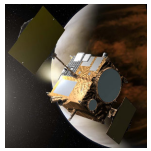
- JAXA mission to Venus - Planet-C (Akatsuki or Venus Climate Orbiter)
- JAXA responsible for the spacecraft construction, launch, mission design and operations
- Science targets:
  - Mechanism of super-rotation
  - Structure of meridional circulation
  - Meso-scale processes
  - Formation of H_2SO_4 clouds
  - Lightning
  - Surface properties and active volcanism
  - Zodiacal light during cruise
- Nominal Launch: May 17, 2010
- Venus Arrival: December 6, 2010
  - 30 hour orbit quasi-synchronous with Venus atmosphere rotation
- Cooperative participation included the DSN and JPL Navigation





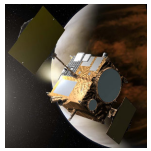
JPL Role

- DSN provides tracking support
  - Tracking outside of Japanese domestic station views (Goldstone and Madrid), including DDOR acquisition
  - Telemetry and command capability
- JPL provides Navigation support – Independent of ISAS Navigation Team
  - Orbit determination and trajectory prediction
  - Navigational tracking data including DDOR
  - Trajectory interface to the DSN
- US Co-Investigators but no US hardware on spacecraft
- Work agreement expressly excludes maneuver support



Requirements

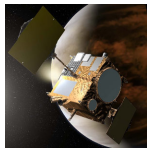
- Orbit determination consistent with 3 km (1σ) altitude uncertainty at Venus Orbit Insertion
- Weekly orbit determination solutions during Venus approach
- Critical orbit determination deliveries for maneuver design, sequence generation, and post-Venus orbit insertion trajectory corrections
  - Typically when the spacecraft is out of view from Japanese domestic tracking assets
- Incorporate DDOR tracking to assess the effect of un-modeled accelerations on the orbit determination process
- Provide real-time three-way Doppler residuals during maneuvers



2010 Primary Mission

- Launch on May 20, 2010 using H-IIA from Tanegashima
- 200 day trajectory to Venus
- One calibration maneuver of the main engine
- Three trajectory correction maneuvers using thrusters
- Venus Orbit Insertion Plan
  - Initially 4 days, then reduced to 30 hours for science acquisition
  - Final science orbit: near equatorial - 300 km x 78700 km (13 Rv)

- Boringly "NOMINAL" through the last pre-VOI tracking pass

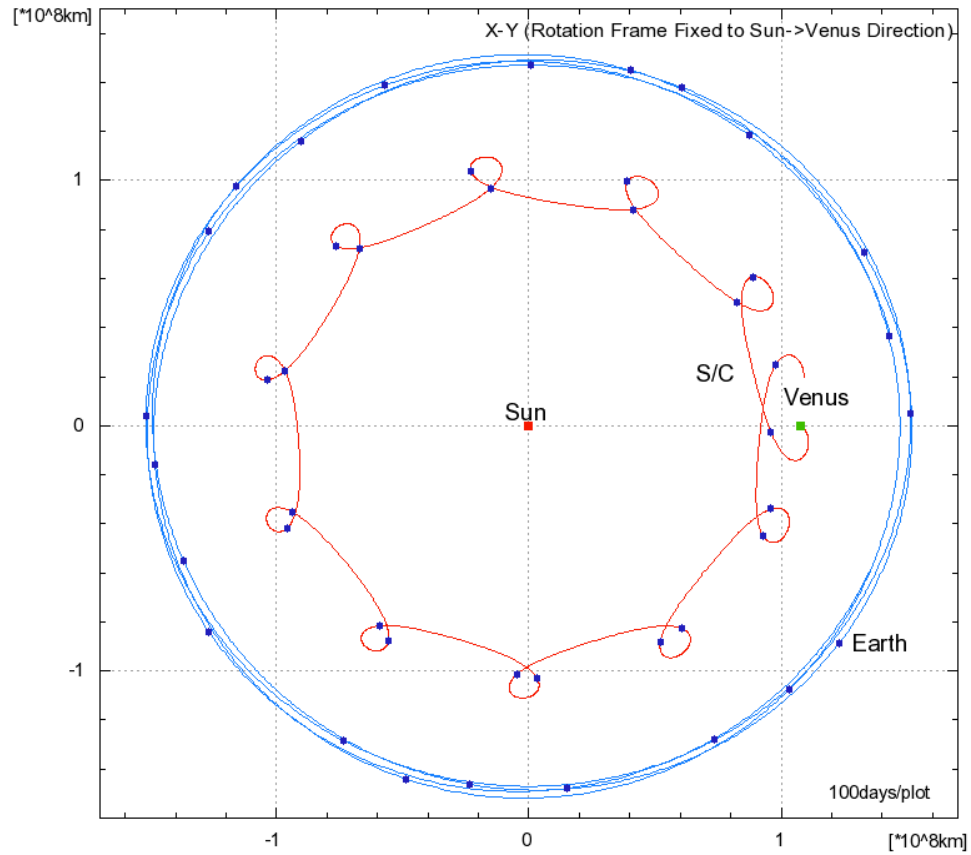


2010 Venus Orbit Insertion Attempt

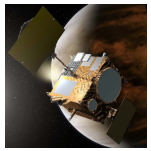
- The VOI was observed to begin nominally and the spacecraft entered occultation as expected
- No signal was observed at the predicted occultation exit time
- Weak intermittent contact on LGA with 8 bps downlink without lock
  - Possible 10 minute spin (safe mode?)
- Blind commanding attempts to reorient S/C and change data rates
- Multiple attempts by DSN to improve link margin using “partial burn” trajectories provided by JPL Navigation
- Two-way Doppler finally acquired 14 hours after VOI attempt
- Data shows 83% VOI under-burn with significant pointing errors
- JAXA abandons attempt to re-establish Venus capture orbit
- Commands transmitted to investigate the anomaly and return S/C to normal operations

Post Anomaly Activity

- OME ground and on-orbit testing in Fall 2011 determined that OME is unusable
  - Engine nozzle either cracked or detached
  - Spacecraft was otherwise healthy
- Future maneuvers use attitude control thrusters in blow down mode
  - Oxidizer dumped to reduce spacecraft mass
- Three maneuvers executed in September 2011 (89, 91 and 64 m/s) successfully target return to Venus in 2015-2016
- DSN and JPL Navigation support suspended in November 2011



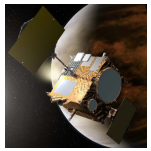
provided by C. Suzuki and. N Ishii



JPL Navigation and DSN Support Resumed in March 2015

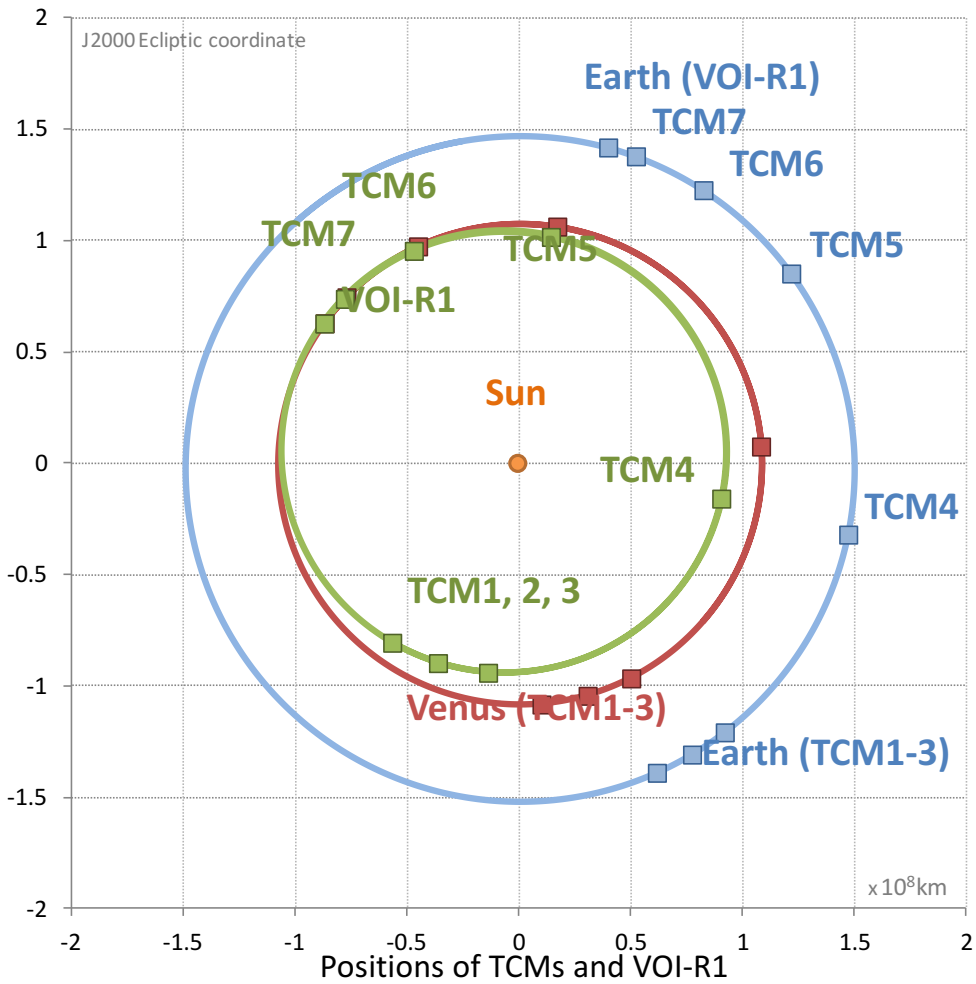
- Completed eight solar orbits since 2010 Venus flyby
- Thermal environment exceeds design specifications for many systems
  - Heat input at perihelion ~ 1000 W/m^2 higher than at Venus orbit
  - RCS thrusters are operating at well above their design limits
- Inertial Reference Unit A: Failed
  - Two backups available
- Data Handling Unit and Data Recorder: Failed
  - Unable to download stored telemetry - work around exists to “dump” data
- Continuous degradation of Solar Array Paddles
  - Plus four discontinuous voltage decreases due to solar flares
- Communication via MGA due to thermal constraints
  - Degraded DDOR precision: from 1.0 nsec to 1.5-2.2 nsec

- Note: Ballistic trajectory impacts Venus on November 21, 2015



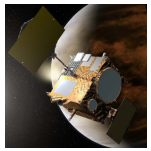
Cruise Orbit Geometry and Events

provided by C. Suzuki and. N Ishii



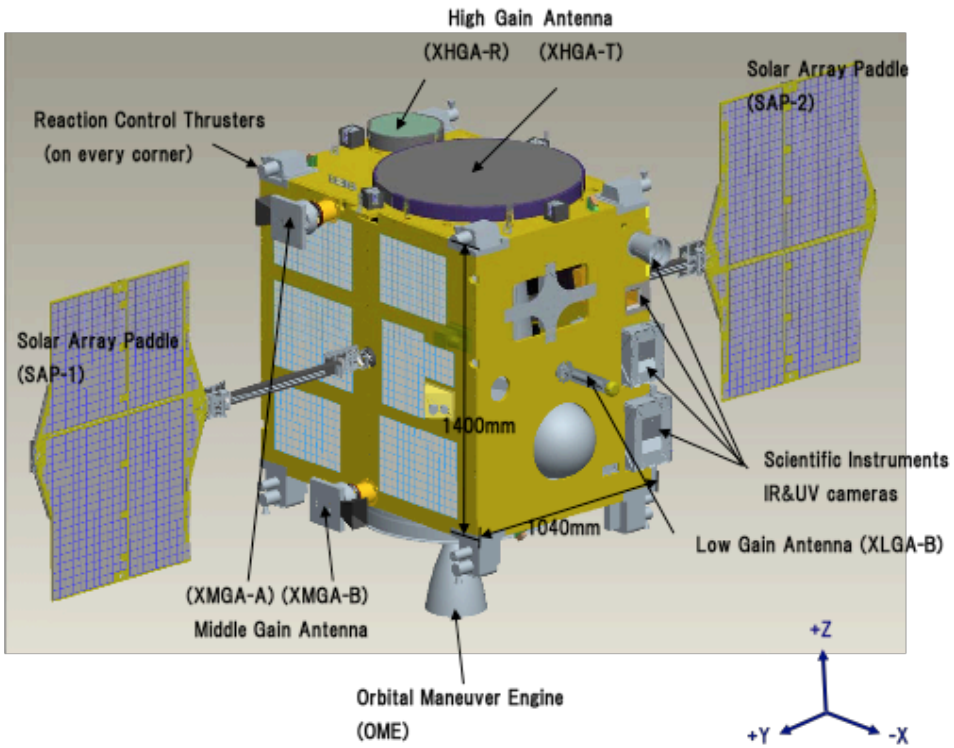
Positions of TCMs and VOI-R1

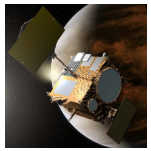
Orbital Events		
JUN	17	TWTA on
JUL	17	TCM1 (18.6 m/s, 95 seconds)
	24	TCM2 (55.3 m/s, 309 seconds)
	31	TCM3 (13.7 m/s, 75 seconds)
AUG	29	Perihelion
SEP	11	TCM4 (1.0 m/s, 6.5 seconds)
OCT	29	TCM5 (TBD)
NOV	19	TCM6 (TBD)
DEC	2	TCM7 (TBD)
	6	Attitude Change (+Z Sun to VOI-R1)
	7	VOI-R1 (198.5 m/s, approx. 1234 seconds)



Planet-C Spacecraft Overview

- Mass: 377.1 kg at resumption of support
- Propulsion:
  - 500 N bi-propellant main engine
  - 8 x 23 N mono-propellant thrusters
  - 4 x 3 N mono-propellant roll thrusters
- Power:
  - Two Solar Array Paddles – one degree of freedom about the Y-axis
- Communications: X-Band
  - HGA : +Z-axis
  - MGA x 2: one degree of freedom about Y-axis
  - LGA x 2: +X and -X-axis
- Attitude control by reaction wheels
- Momentum wheel unloading once per week
- Dynamically clean spacecraft

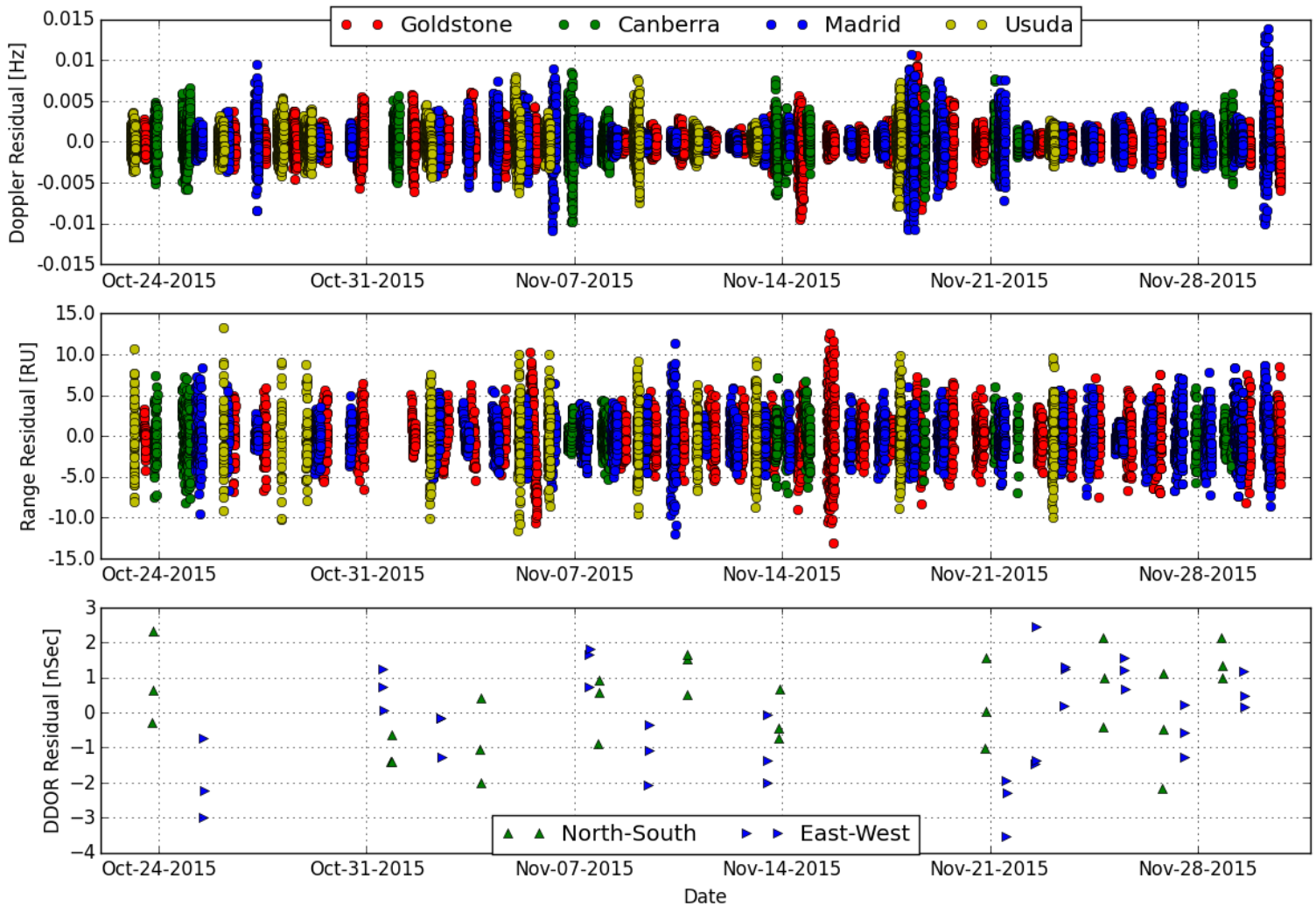


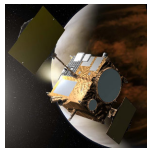


Tracking Data Characteristics

- DSN tracking data : Doppler, sequential range and DDOR
- ISAS tracking data: Doppler, regenerative PN ranging and DDOR
- No DDOR tones: using telemetry side-bands
- Baseline data weights DSN and ISAS tracking
  - Doppler: 0.2 mm/sec
  - Range data: 3 meters
  - Deweighted Doppler and range to noise level as appropriate
  - DDOR: 1.5-3.0 nsec
- Calibrations: troposphere and ionosphere for DSN and ISAS stations
- Occasional noisy data due to solar flares and CME activity
- Demonstration DDOR co-observations conducted using DSN Goldstone, DSN Canberra, and Japanese Usuda tracking stations
  - June 16, July 7, July 20 and July 27
  - Delivery of raw VLBI recorded data to JPL: 6 hours
  - Correlation time at JPL: 2 hours

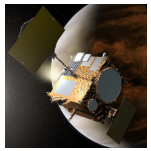
Cruise Tracking Data





Orbit Determination Filter Assumptions

Error Source	Estimate Type	A Priori Uncertainty (1σ)	Comments
2-way Doppler weight (mm/s)	--	0.2	
Sequential range weight (m)	--	3	
Regenerative PN range weight (m)	--	3	
DDOR weight (ns)	--	1.5-3.0	
State Position (km)	Estimate	1e-6	
State Velocity (km/s)	Estimate	1	
Solar Radiation Pressure Scale Factor (% of total)	Estimate	10	
Maneuver thrust, RA and Dec (%, deg, deg)	Estimate	2,2,2	
Desat Event XYZ Δv (mm/sec)	Estimate	0.5,0.5,1.0	
Future Desat Event XYZ Δv (mm/sec)	Consider	0.5,0.5,1.0	
Range bias – sequential and regenerative PN (m)	Stochastic	5	Per Pass
Ionosphere – day/night (cm)	Stochastic	75/15	White Noise, Per Pass
Troposphere – wet/dry (cm)	Stochastic	1/4	White Noise, Per Pass
Pole X,Y (cm)	Consider	10.0,10.0	1.5e-8 radians
UT1 (cm)	Consider	10.0	0.3e-3 sec
Earth GM (km^2/sec^2)	Consider	1.4e-3	
Venus GM (km^2/sec^2)	Consider	6.0e-3	
Earth-Venus Ephemeris	Consider	Formal DE421 covariance	
DSN station Locations (km,deg,km)	Consider	Formal covariance	~5cm
JAXA station Locations (km,deg,km)	Consider	Formal covariance	~10cm
Quasar Locations - RA, Dec (nrad)	Consider	1	

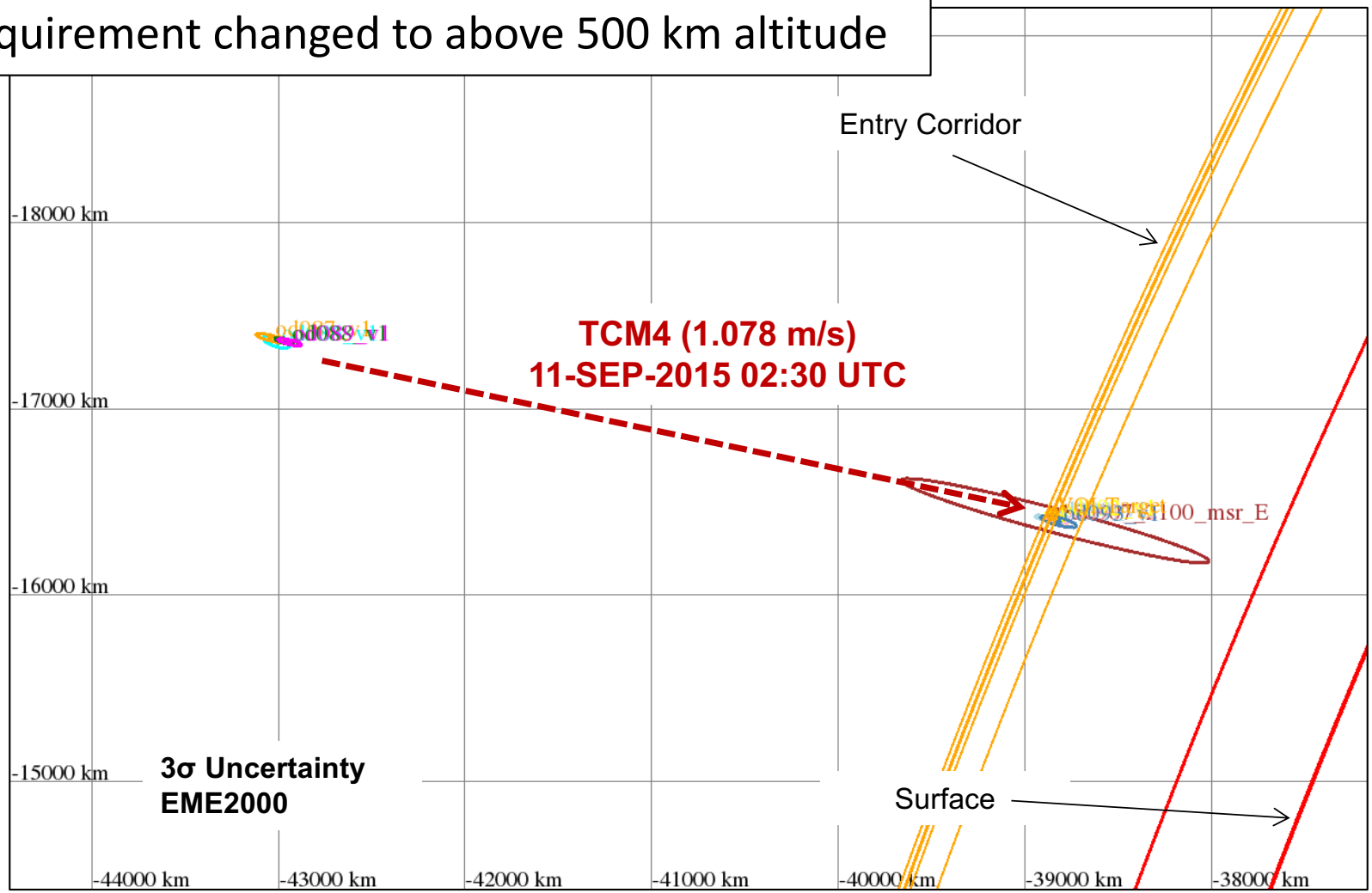


Approach Maneuver Details

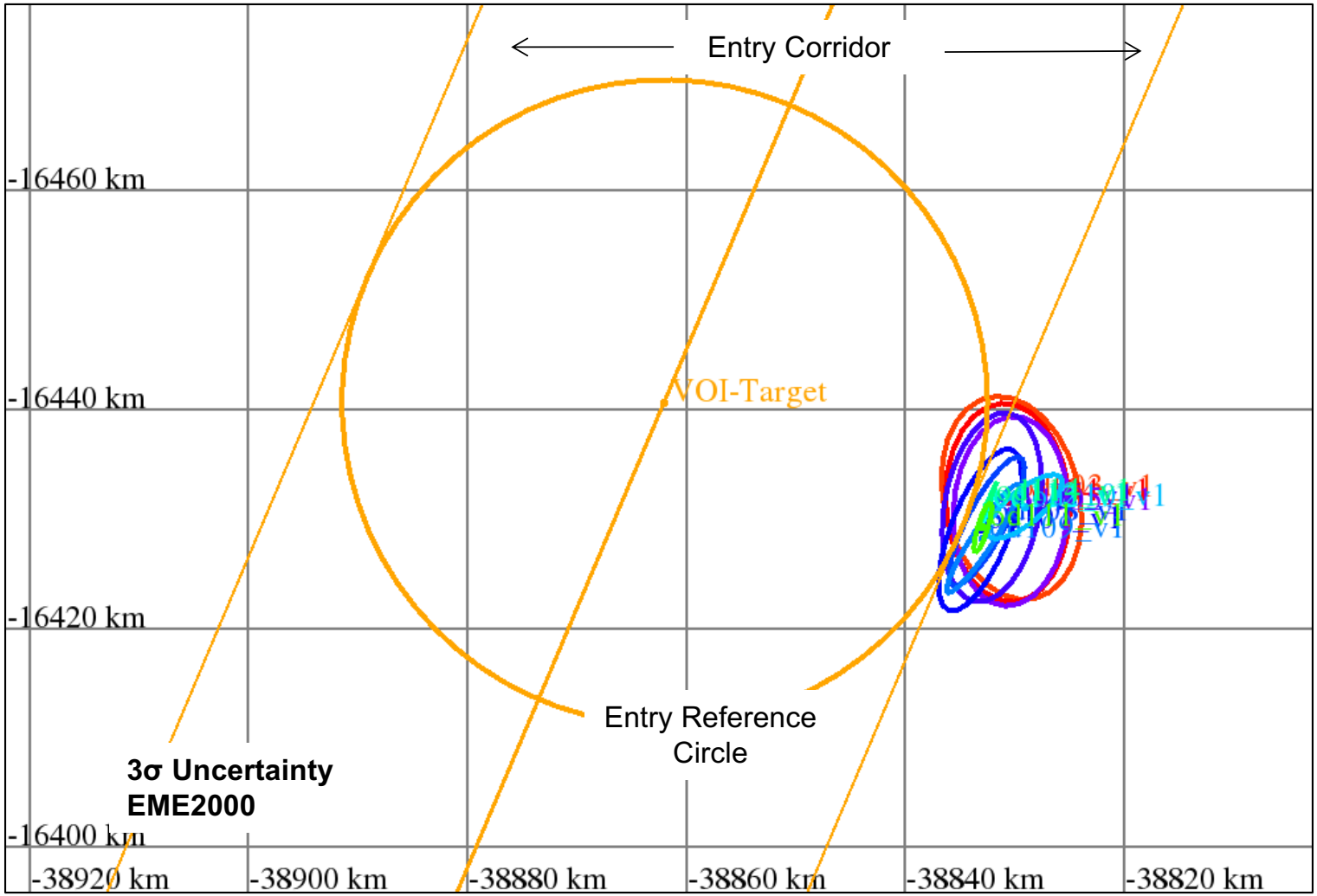
- TCM1, TCM2 and TCM3 executed in mid-July to change approach geometry and arrival date to December 7, 2015
  - 19, 53, 16 m/s respectively
- Penalty to delay the maneuver 1-2 days: ≈1 m/s
- Four RCS 23 N thrusters in blow down mode (approx. 18 N each)
- Maneuver design and thrust table updated following each burn
- 6th order thrust polynomial model matches design ΔV to 1 m/s
- Duty cycle added improve accuracy of maneuver performance
- Slew on RCS: TCM start – 30 minutes to TCM end + 10 minutes
- Communications mode: LGA-A/B, with marginal link margin for two-way Doppler from Usuda during maneuver execution
- DSN three-way Doppler tracking from Canberra for TCM1 and TCM3
- Real-time three-way Doppler residuals provided by JPL Navigation for TCM3
- TCM4 cleanup maneuver executed in mid-September to correct approach trajectory (1 m/s)

TCM4 OD Summary

- Requirement changed to above 500 km altitude

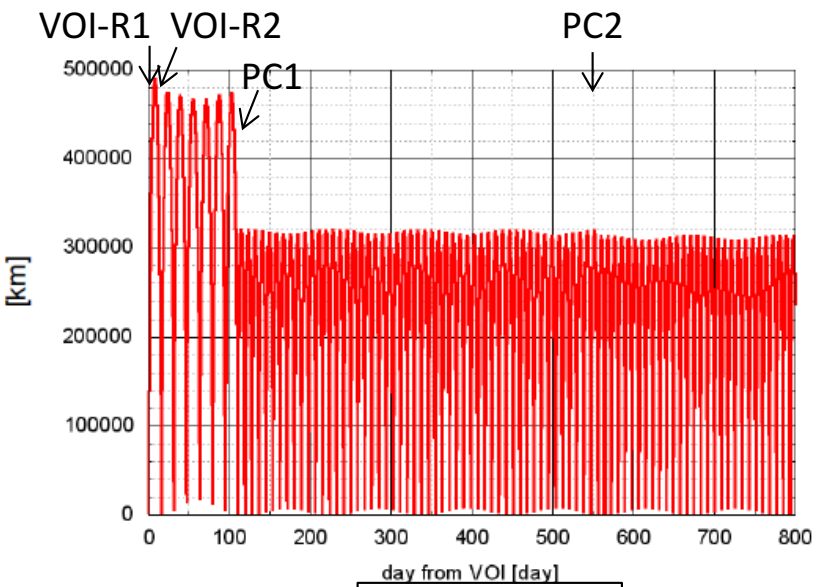


B-Plane History for Final Two Weeks

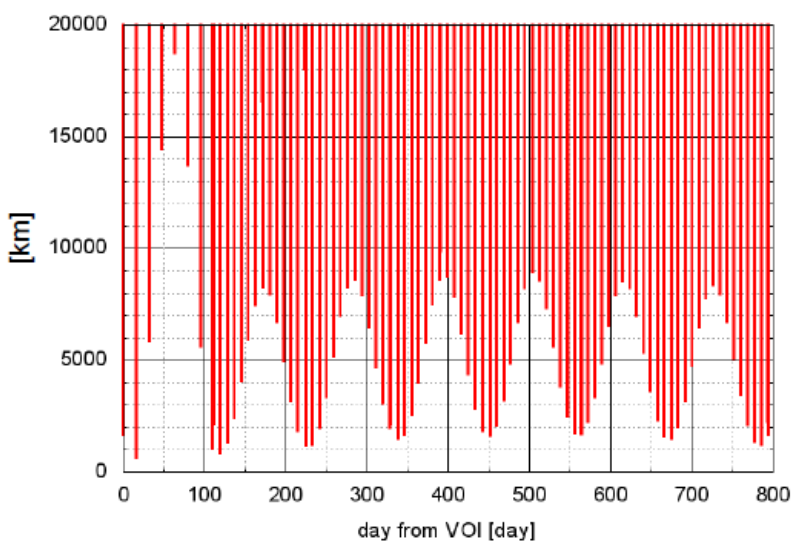


Venus Orbit Phase Design Geometry and Events

provided by C. Suzuki and. N Ishii



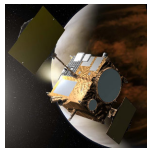
Periapsis Altitude



Apoapsis Altitude

Year	Month	Day	Orbital Events	Ha [mil.km]
2015	DEC	7	VOI-R1 (198.5 m/s, approx. 1234 seconds)	0.49
		22	VOI-R2 (2.0 m/s, 12 seconds): one orbit after VOI-R1	0.48
2016	MAR	26	Phase Control 1 (29.4 m/s)	0.33
	NOV	10	PC2 (0.5 m/s)	0.33
2017	JUN	16	PC3 (6.0 m/s)	0.31

Requirement: Altitude of Periapsis: 3 km 1σ

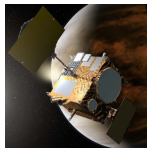


Venus Orbit Insertion Design

- VOI-R1
  - PLC escapes Venus for VOI-R1 less the 174 m/s
  - PLC has long apoapsis eclipses for VOI-R1 more than 206 m/s (>150 min)
  - Select nominal VOI-R1 magnitude of 198 m/s using AT thrusters
    - Post insertion period = 14 days
  - Maneuver errors between +5 to -10 percent of nominal, plus small correction at VOI-R2 (second periapsis) result in an acceptable short term post insertion trajectory

- VOI-R1c
  - Monitor VOI-R1 Doppler and telemetry in real-time
  - Assess VOI-R1c performance based on any observed VOI-R1 and attempt a correction maneuver using AB thrusters
  - Contingency assumptions:
    - VOI-R1 is interrupted or does not execute
    - 3-axis attitude control is maintained (not in safe mode)
    - Slew to VOI-R1c attitude is nominal
    - Telemetry and commanding are operational
  - VOI-R1c commands will be uplinked and maneuver executed

- Additional phase control maneuvers in 2016 (reduce apoapsis altitude) further control eclipse duration

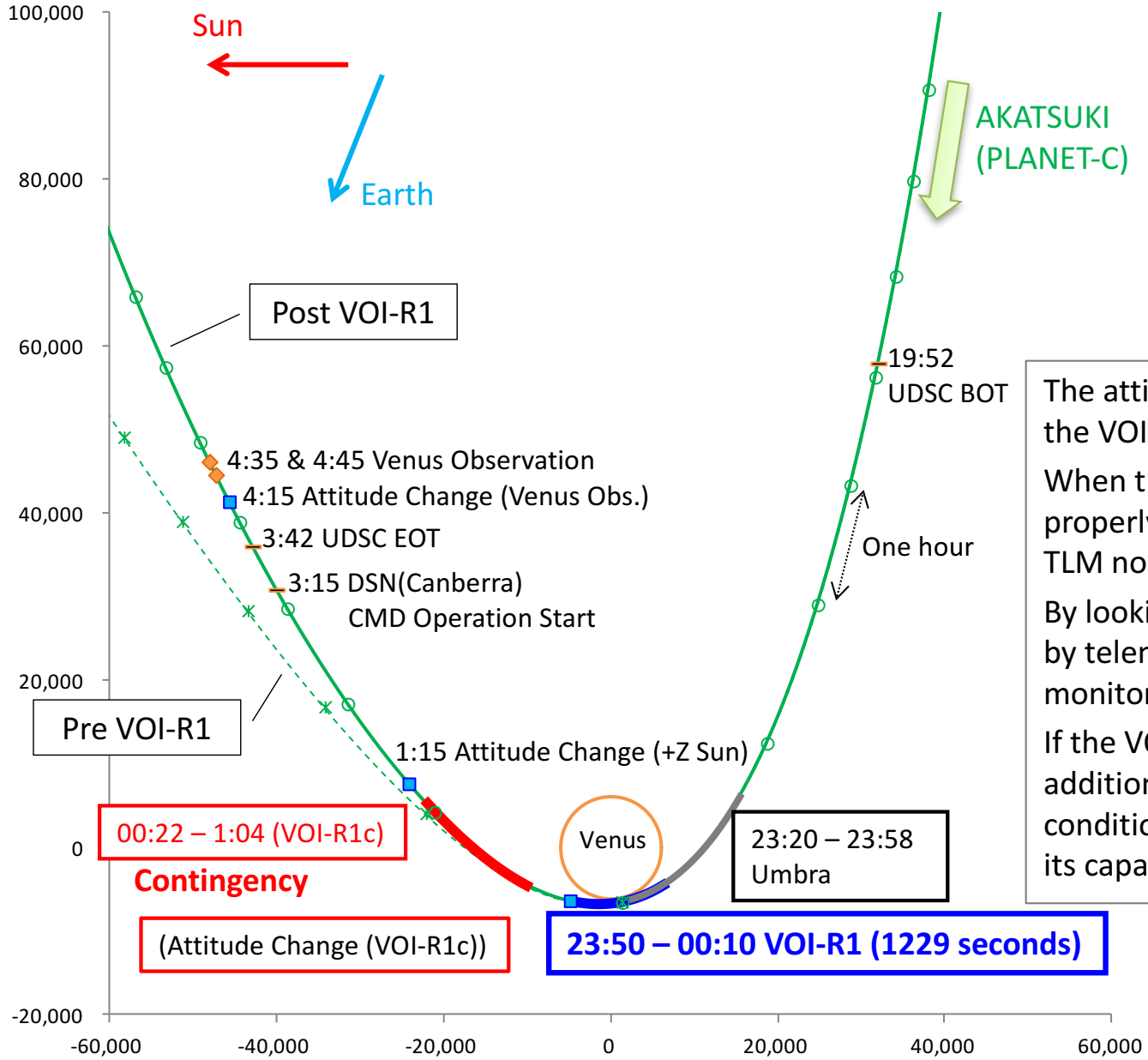


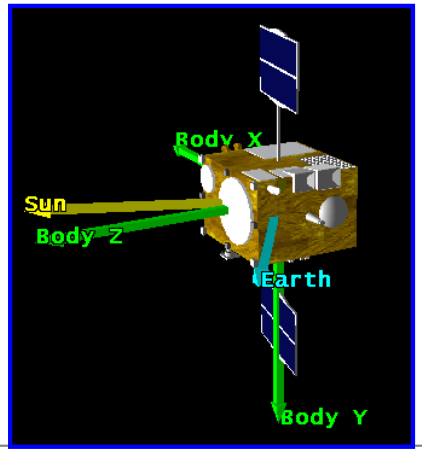
Venus Orbit Insertion Support Plan

- VOI-R1
  - Burn Epoch: December 6, 2015 23:51:27 UTC
  - 198 m/s using thrusters (1229 seconds – 20:29)
  - Range to S/C: 1 AU – OWLT = 499 seconds – 8:19)
  - Entire burn is visible & burn/noburn pointing difference is within the 70m half-beam width for 18 hours ☺
  - First seven minutes in eclipse
- JAXA and JPL monitor Doppler residuals in real-time
  - DSS-43 will be three-way with Usuda
- VOI-R1c
  - December 7, 2015 00:24 UTC
  - Initiated via ground command based on R/T Doppler residuals
- Other Events
  - Venus occultation (~December 6 15:00-19:00 UTC)
  - Lunar occultation (~December 7 16:20-18:10 UTC)

Venus Orbit Insertion Nominal Operation

provided by C. Suzuki and. N Ishii





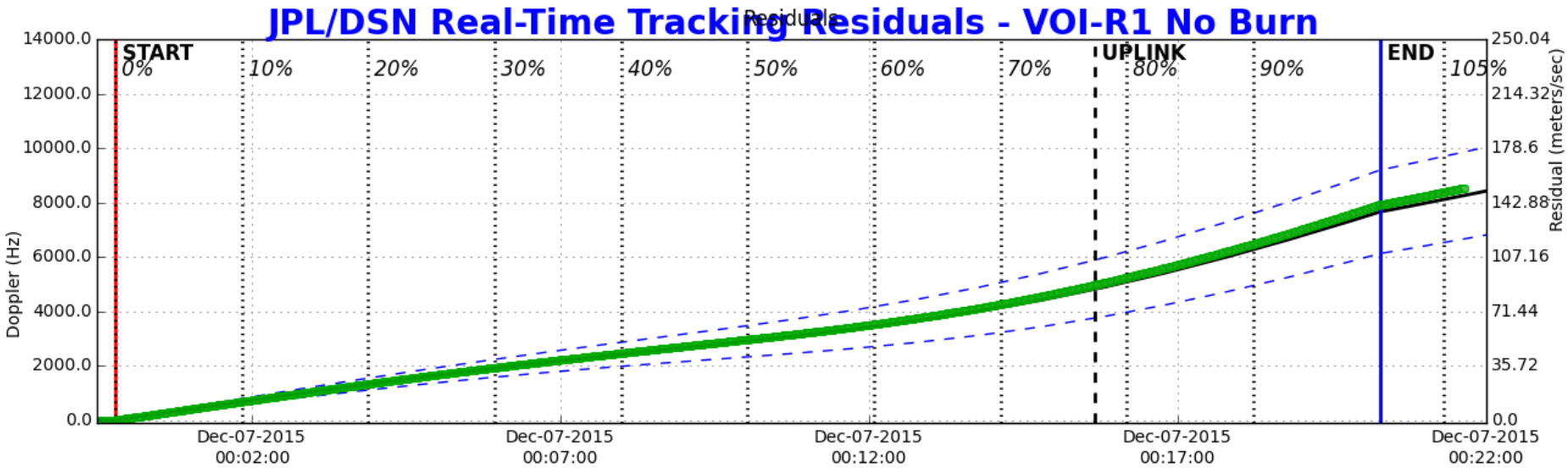
The attitude will be changed one day prior to the VOI-R1.

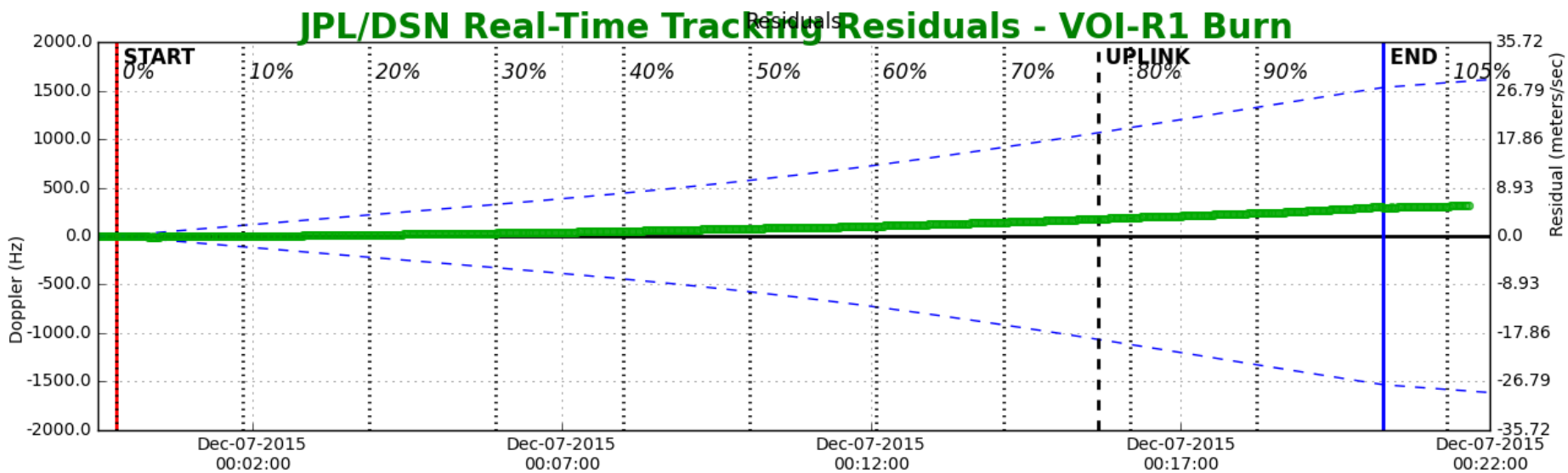
When the stored commands (Timeline) work properly, VOI-R1 will be accomplished with no TLM nor CMD operation on the day of VOI-R1.

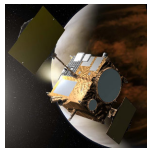
By looking at the Doppler and injection counts by telemetry, the status of VOI-R1 will be monitored.

If the VOI-R1 is interrupted, we plan an additional maneuver (VOI-R1c) under the condition when we can judge that PL-C has still its capability.

VOI-R1 Real-Time Doppler Residuals

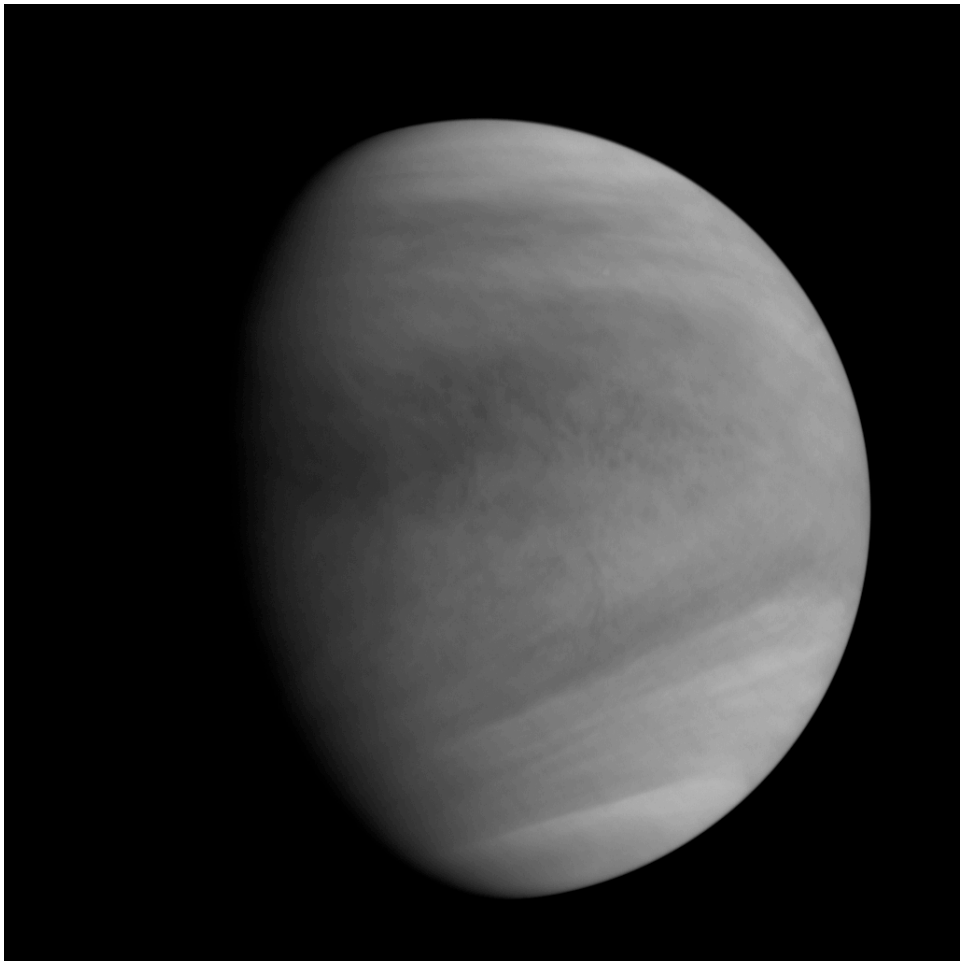






Post Orbit Insertion Status

- VOI-R1 executed nominally – Planet-C in orbit about Venus
  - Maneuver performance:
    - 199.3 m/s - 4.2% over burn
    - 1.5 degree pointing error
    - 14.0 day period vs. planned 16.6 day period
    - VOI-R1c not needed
- Venus observations conducted shortly after orbit insertion
- VOI-R2 executed nominally on December 20, 2015 with DSN Goldstone 34m station uplinking
  - Maneuver performance
    - 14.7 m/s - 0.1% underburn burn
    - 1.1 degree pointing error
- Science orbit established (10.6 day period)
- PC1 maneuver executed nominally on April 4, 2016 to control eclipse duration
  - Maneuver performance: 2.2 m/s
- JPL Navigation and DSN support ends on April 16, 2016

Hello Venus…

- Planet-C is the only spacecraft currently operating in Venus orbit